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Some preliminary tests of steel frames under reversed loading have recently been conducted at Lehigh University as an adjunct to the project, "Welded Continuous Frames and Their Components" under sponsorship of the AISI and others. In these tests it has been possible to apply one or two cycles of reversed loading to frames that previously had been loaded to maximum load and then deformed through additional plastic displacements. Although the starting deformations for the reverse load sequences were quite large, the data collected should be of interest in comparison with other test results being presented in this session on seismic action of structures. The results to be shown have been obtained by Mr. Erol Yarimci, Research Instructor, in a program being supervised by Dr. Le-Wu Lu, the results of which will be reported in detail in the near future.

In the upper left portion of Fig. 1 is shown the loading and corresponding mechanism for the first of these preliminary tests. Six-in. and eight-in. WF shapes were used in this three-story, single-bay frame. Story heights were 10 ft. and the bay spacing 15 ft. Vertical load was applied to the beams, and after reaching the predetermined maximum value (1.30 times service load), it was maintained constant during subsequent application of horizontal loads. All loads were applied with hydraulic jacks. The axial force in the columns was about one-third the full yield value in the lower story.

The results of the test are shown by the solid curves in the main part of Fig. 1. These are shown in relationship to the theoretical predictions for static load, since the main object of the original test program was to test out the theory under a single application of load. The upper dotted curve is the theoretical prediction of horizontal load vs. lateral deflection at the roof level according to the simple plastic theory. The lower theoretical curve includes the influence of column deflection on the behavior. (As the frame moves through a displacement, Δ, there is an increase in column moments which is a function of the axial force in the column times the displacement. Hence the term, "P - Δ" effect.)

The result? Under the first direct application of load the test curve was between the theoretical curves.

The most interesting and even more favorable result, however, was the considerable increase in load (and corresponding increase in energy) that was observed when the horizontal load was reversed after the first application of load was removed. In the first phase the load was about 3 kips. But in the reversed phase it was 4 kips, or an increase of one-third. With such a promising results it was evident that a similar loading should be attempted at the next opportunity.

This next opportunity presented itself at the conclusion of the Plastic Design Summer Conference held at Lehigh University in August 1965. The loading and failure mechanism for the three-story, two-bay frame are shown in Fig. 2. Again the story height was 10 ft. with bay spacing of 15 ft. The members used for the columns were 6WF25 shapes, 12B16.5 members were used for the floor beams and 10B15 for the roof beams. Bracing was supplied to prevent deformation out of the plane of the frame. Hinges would be expected to form at column bases, at the leeward end and at the windward load point for each beam. Axial loads can cause a significant increase in column moments (as noted above); in the exterior columns at failure the axial thrust in the first story was about 25% of full yield and in the interior column this value was 50%.

Figure 3 shows the frame at the end of "Phase 1", a one-time application of side load to the right. The column-top displacement was about 9 1/2" (the deflected shape is evident in the photograph), and it was from this position that the cyclic testing was started. Figure 4 shows the hinge that formed (as predicted) at the left load point of the lower left beam during Phase 1. The local buckling of the compression flange was first observed at "Load 13" (see Fig. 5 which follows). There was no evidence that it weakened the frame for the deformations applied.

The dotted lines in Fig. 5 are predictions based on the same two theories described in connection with Fig. 1. Again the test curve came between the two curves, although closer to the lower value for the Phase 1 loading. The total deflection was 9.4". Since plastic hinges had already formed under vertical load prior to application of the horizontal load, then the "ductility factor" would be very large indeed. However, due to the nature of the loading it could not be assigned a value that would have meaning in relation to other theoretical predictions.

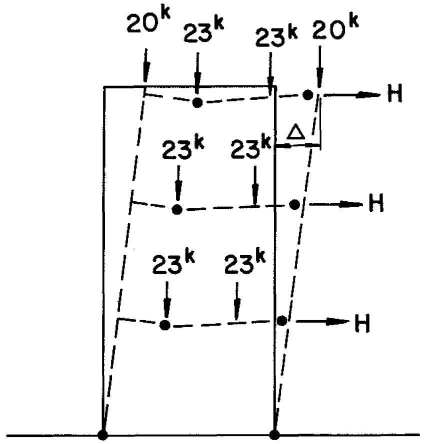
Phase 2 began with the application of horizontal load in the reverse direction (to the left). Loading continued until the "stroke" capacity of the load simulators had been exhausted. As shown by Fig. 5, a significant increase in load and energy absorption was again observed in this frame test (compare 8 kips for Phase 2 with 5 kips for Phase 1). A similar observation was made in Phase 3 (which consisted of a second application of load to the right). In this case the maximum horizontal load was 7 kips, compared with about 5 kips on the first loading. The test was terminated due to difficulties with a bracing link.

One basis for comparing the energy absorbed during the various phases is to compare the energy absorbed for equal displacement from zero horizontal load, (9 1/2 inches). The approximate results are as follows: Phase 1, 40 kip-in; Phase 2, 60 kip-in.; Phase 3, 51 kip-in.

What accounts for the increase in energy absorption? Several factors can be suggested tentatively. One of these is the displacement effect. When the frame deforms, the beams "drop"; then when the load is reversed, these loads must be lifted again. This would require an increase in load. Another factor could be strain-hardening on successive cycles of load application.

These results, although very preliminary, are very encouraging. It is now the plan of the research workers at Lehigh to proceed with tests of frames designed specifically for repeated loading effects. Rather than apply the initial load phase to maximum load followed by large deformations, a promising approach should be to consider what cyclic action and deformation capacity would be required (considering, for example, the work of Berg at Michigan--as described elsewhere in these Proceedings), and to start the cyclic tests with significantly smaller deflections than those which were necessarily used in the two tests just noted.

It may well be that the effect of selecting smaller initial displacements will mean a closer parallel with Popov's results described in an earlier paper which show very "stable" hysteresis loops, rather than the increases observed in these tests. In the meantime it is encouraging to know that there is such a significant increase in energy-absorbing capacity for very large deformations when compared with that absorbed on the first cycle.



Horizontal Load-Sway Relationship From First Three Story One Bay Frame Test

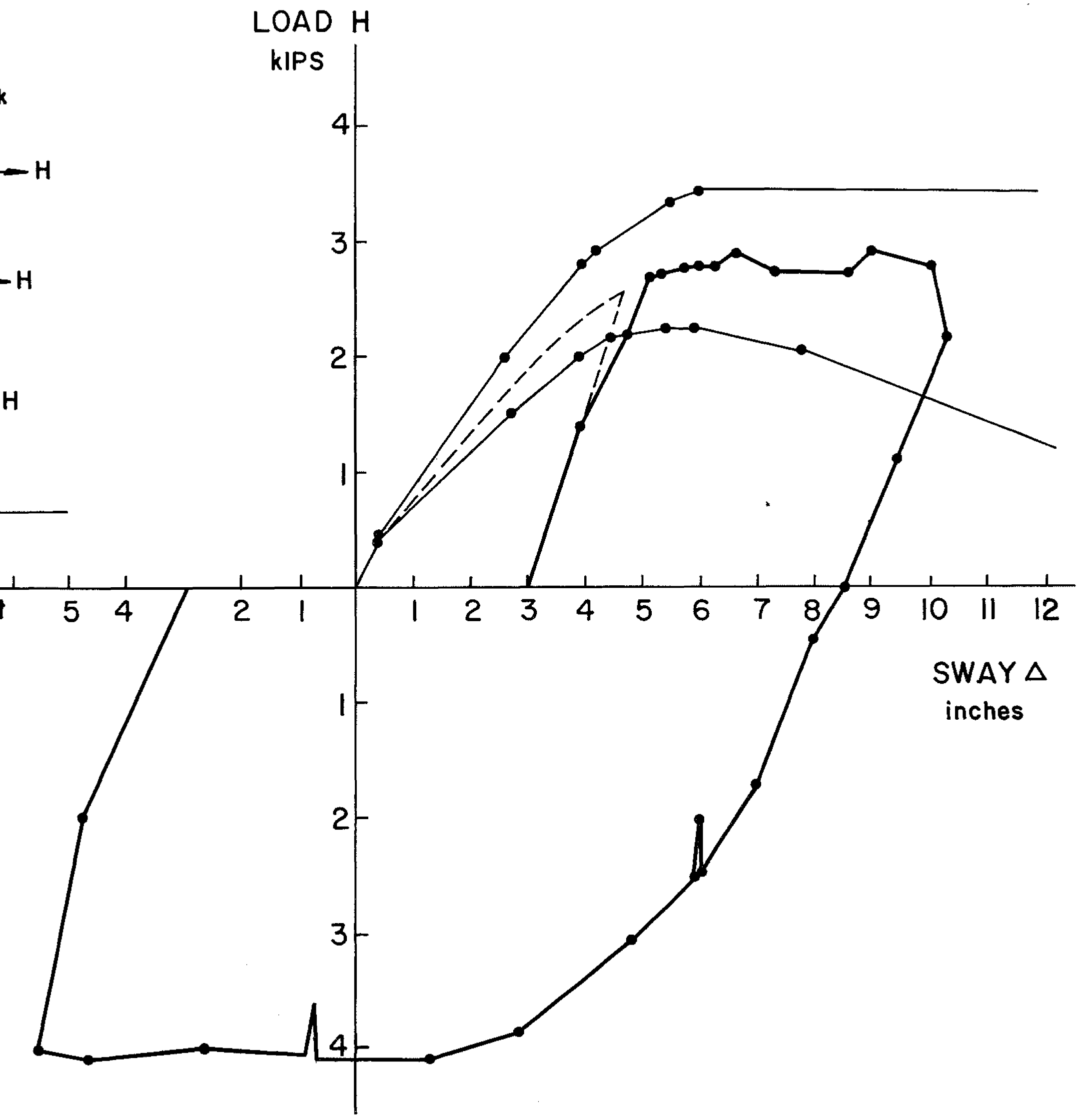


Figure 1

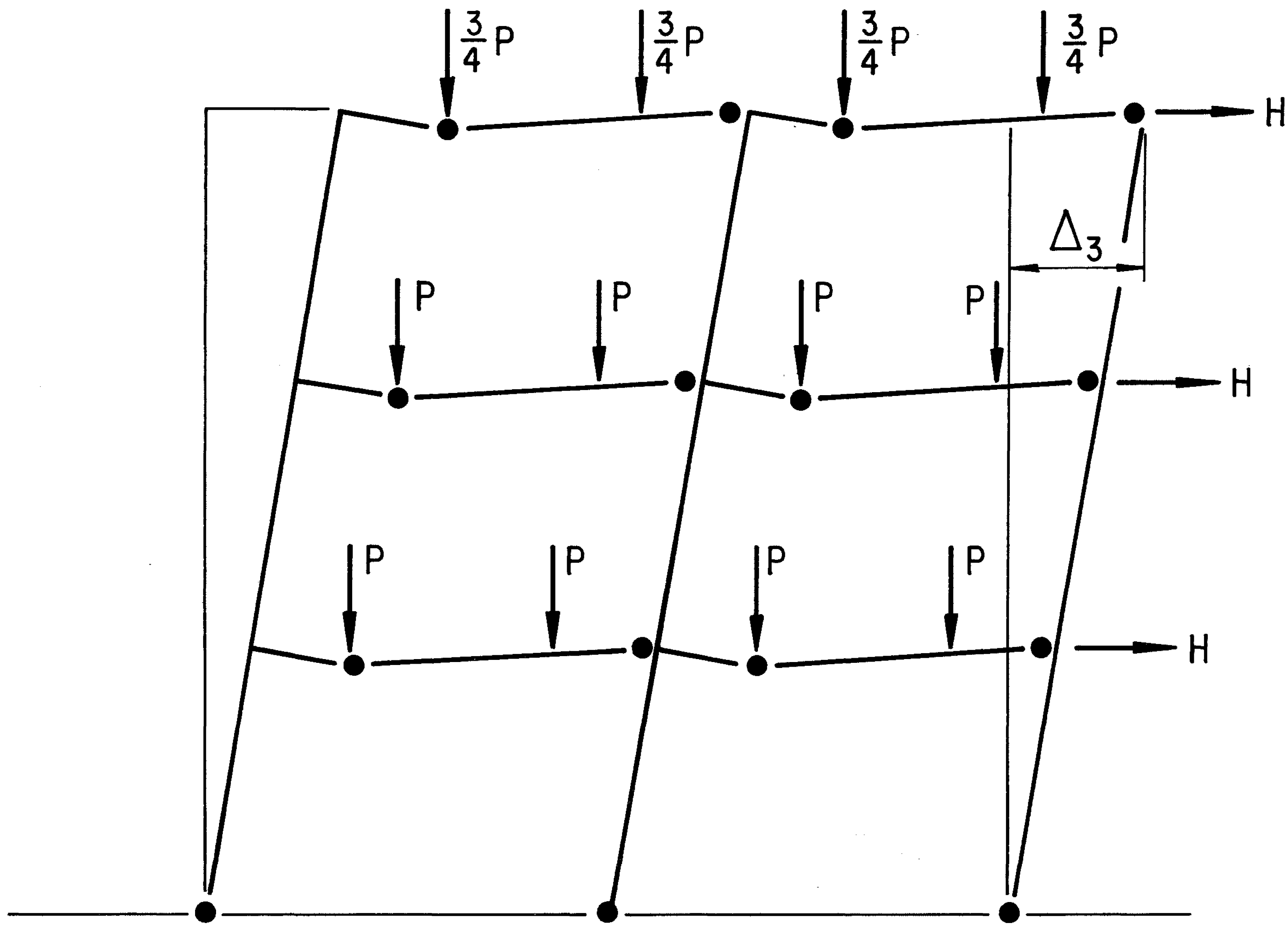


Figure 2

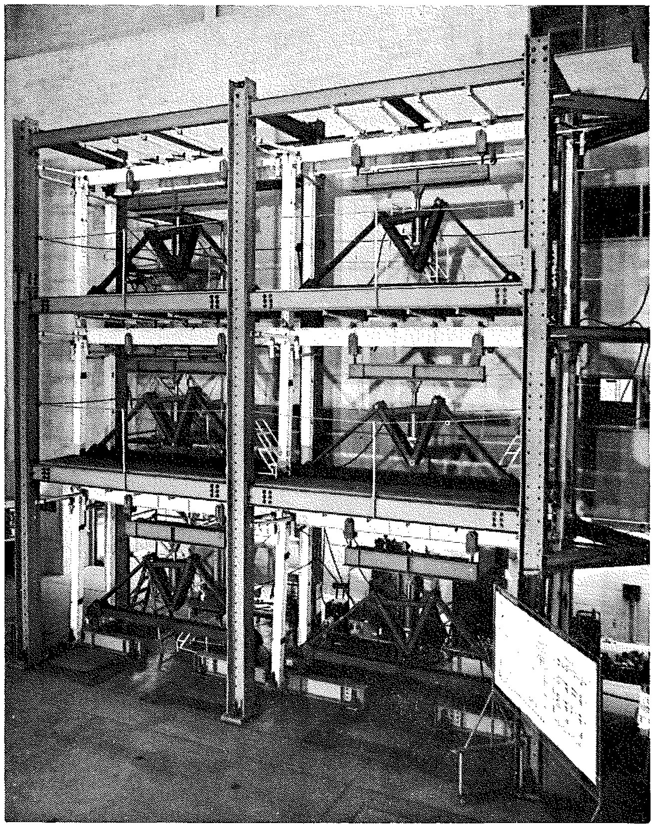


Figure 3

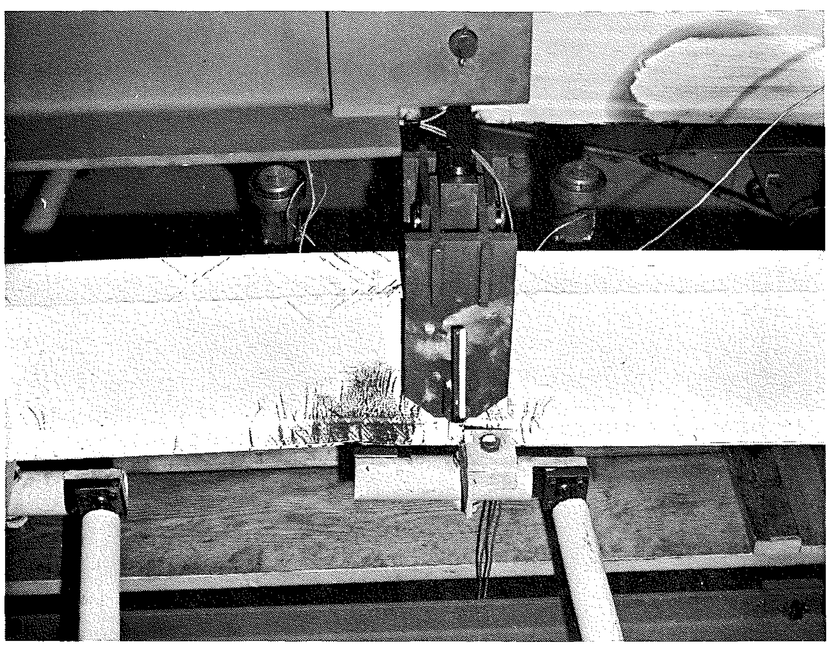


Figure 4
(upside down)

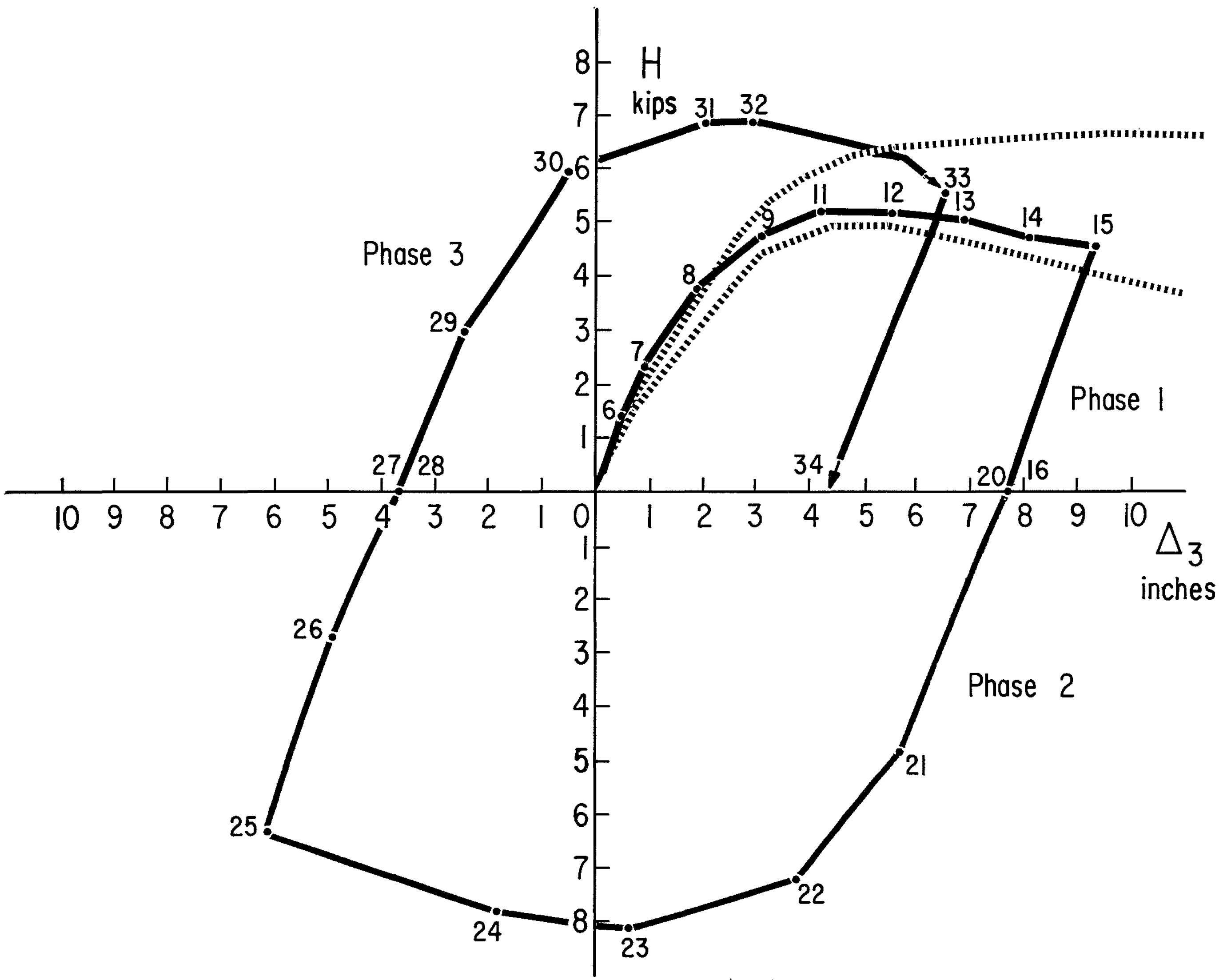


Figure 5